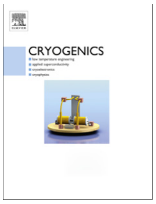
Cryogenics 81 (2017) 83–92

Contents lists available at ScienceDirect

Cryogenics

journal homepage: www.elsevier.com/locate/cryogenics



Research paper

Cryogenically cooled ultra low vibration silicon mirrors for gravitational wave observatories

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ARTICLE INFO

Article history:
Received 29 October 2016
Received in revised form 7 December 2016
Accepted 9 December 2016
Available online 18 December 2016

Keywords:
Low vibration cryogenics
Gravitational waves
Feedback control

ABSTRACT

Interferometric gravitational wave observatories recently launched a new field of gravitational wave astronomy with the first detections of gravitational waves in 2015. The number and quality of these detections is limited in part by thermally induced vibrations in the mirrors, which show up as noise in these interferometers. One way to reduce this thermally induced noise is to use low temperature mirrors made of high purity single-crystalline silicon. However, these low temperatures must be achieved without increasing the mechanical vibration of the mirror surface or the vibration of any surface within close proximity to the mirrors. The vibration of either surface can impose a noise inducing phase shift on the light within the interferometer or physically push the mirror through oscillating radiation pressure. This paper proposes a system for the Laser Interferometric Gravitational-wave Observatory (LIGO) to achieve the dual goals of low temperature and low vibration to reduce the thermally induced noise in silicon mirrors. Experimental results are obtained at Stanford University to prove that these dual goals can be realized simultaneously.

1. Introduction

Gravitational waves were directly observed for the first time [1,2] by the Advanced Laser Interferometer Gravitational-wave Observatory (LIGO) [3,4] in 2015, 100 years after Einstein first described them [5]. Advanced LIGO is expected to be sensitive to waves coming from binary black hole inspirals, binary neutron star inspirals, stellar collapses, pulsars, and a stochastic background of radiation from the early universe. So far, the two confirmed detections made by Advanced LIGO in its first four month observing run were from binary black hole inspirals.

Advanced LIGO's observations are limited in part by the displacement noise of the mirrors in the interferometer. While Advanced LIGO is expected to continue making significant observations of astrophysical events, more advanced observatories will nonetheless be required in order to realize the potential of the astronomy and astrophysics obtainable with gravitational waves.

The lowest noise frequency band of Advanced LIGO is designed to be limited by thermally driven vibrations of the four 40 kg, 34 cm diameter, room temperature, fused silica test mass mirrors. This noise can be significantly reduced through a combination of lowering the mirrors' temperatures to a cryogenic regime, selecting mirror materials with low mechanical loss, and using larger mirror diameters. The next generation of LIGO, LIGO Voyager, plans to upgrade the existing facilities, in part, with a switch to 44 cm diameter, 124 K ± 2 K, silicon mirrors between 150 kg and 200 kg. Silicon is beneficial at cryogenic temperatures because unlike fused silica, its mechanical loss decreases with temperature. 124 K is chosen because silicon's thermal expansion coefficient crosses zero [6]. This zero crossing eliminates the thermoelastic component of the thermal noise, and also minimizes radius of curvature changes induced by temperature gradients. Also unlike fused silica, cryogenic silicon has very high thermal conductivity. Higher thermal conductivity permits higher laser powers because the thermal lensing of the mirror is reduced, and because getting absorbed heat out is easier. High laser power reduces high frequency quantum noise (shot noise). LIGO Voyager will have about 3 MW of power on the mirror, while Advanced LIGO will have about 750 kW. Because of these features of silicon at 124 K, the LIGO Voyager noise will be about 3 times smaller than Advanced LIGO over a wide frequency band.

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http://dx.doi.org/10.1016/j.cryogenics.2016.12.004
0011-2275/

Fig. 1 shows a prediction for the displacement noise performance for a possible LIGO Voyager interferometer in black. For reference, the Advanced LIGO design is shown as the dashed cyan curve. The other curves show the contributions to the total LIGO Voyager noise. The mirror thermal noise, in yellow, is achieved by utilizing 124 K silicon mirrors. The precise values of the LIGO Voyager curves will depend somewhat on design choices still to be made, but these curves are a good representation for the work presented here.

The mirror's low temperature must be achieved without increasing its mechanical vibration, i.e. without increasing the blue curve in Fig. 1. Additionally, any cryogenic components near the mirror must also have low mechanical vibration due to noise coupling through scattered laser light. Small components of the interferometer laser will scatter off the mirrors, hit nearby surfaces, and then recombine back into the interferometer. If these surfaces are vibrating they will impose both a phase shift on the light, and also cause disturbances in the light's radiation pressure on the mirror. Both effects will cause increased noise to appear in the interferometer.

Other future gravitational wave observatories such as KAGRA in Japan [7] and The Einstein Telescope (ET) in Europe [8] plan to use cryogenic mirrors as well, but at the colder temperatures of 20 K and 10 K respectively. ET, uniquely, plans to use both 10 K and room temperature mirrors. The different temperature regimes emphasize different frequency bands of performance and different engineering challenges. The lower temperatures help further reduce thermal noise, visible below about 100 Hz. However, high laser power on the mirror to help reduce shot noise above 100 Hz is not feasible at these temperatures. Lower temperatures do permit smaller mirrors, since a large laser radius is not needed to average out thermally induced oscillations seen in the mirror coating and since the laser's radiation pressure noise will be weaker (low frequency quantum noise). Cooling the mirrors this low does require building a conductive heat path into the mirror's vibration isolation system, which imposes a significant design challenge, as the heat path can compromise the vibration.

The 3 MW of power LIGO Voyager intends to use is much greater than the 400 kW for KAGRA's and 18 kW for ET's cryogenic mirrors. This higher laser power permits lower shot noise. Additionally, the warmer cryogenic temperatures in LIGO Voyager permit radiative cooling of the mirrors, so a conductive heat path does not need to be integrated into the vibration isolation system. Larger diameter and more massive mirrors are needed, however, to help minimize the effect of mirror thermal noise and radiation pressure. The high laser power does increase the potential for light scattering noise, so engineering work is required to keep this under control.

The contribution of this paper is to propose for the first time a sufficiently low vibration cryogenic system for the 124 K silicon mirrors intended for future LIGO Voyager interferometers. Section 2 describes the proposed cryogenic layout. Section 3 describes the experimental setup at Stanford, used to demonstrate that sufficiently low levels of vibration are feasible. Section 4 presents and analyses the results from this experiment. Finally, Section 5 presents concluding remarks.

2. Proposed LIGO voyager cryogenic layout

2.1. Overview

Fig. 2 illustrates the layout of a LIGO mirror vacuum chamber with the proposed cryogenic infrastructure. The vacuum enclosure and the vibration isolation table will be reused from Advanced LIGO. The layout of the cryogenic components is intended to be general in scope. Details such as the precise dimensions of the shields and the materials used will be determined in future work.

The mirrors are between 150 kg and 200 kg of 124 K ± 2 K silicon. To provide the necessary vibration isolation, the mirrors are the bottom stage of a four stage suspension, which hangs from an actively controlled vibration isolation table. The isolation table is a two stage mass-spring system that feeds back on-board inertial sensor signals to actuators in order to achieve favorable isolation performance below 10 Hz. The four stage suspension is a passive isolation system providing isolation above 10 Hz.

To achieve the desired mirror temperature without compromising this vibration isolation system, the cryogenic system and vibration systems are physically separate. As shown in Fig. 2, the cryogenic system consists of a dual heat shield system that surrounds the lower part of the suspension with a non-contacting inner shield at 83 K and an outer shield at 80 K. The inner shield maintains the mirror temperature purely by radiatively absorbing about 5 W. 5 W is the expected steady state heat load on the mirror, primarily due to absorption of the interferometer laser into the

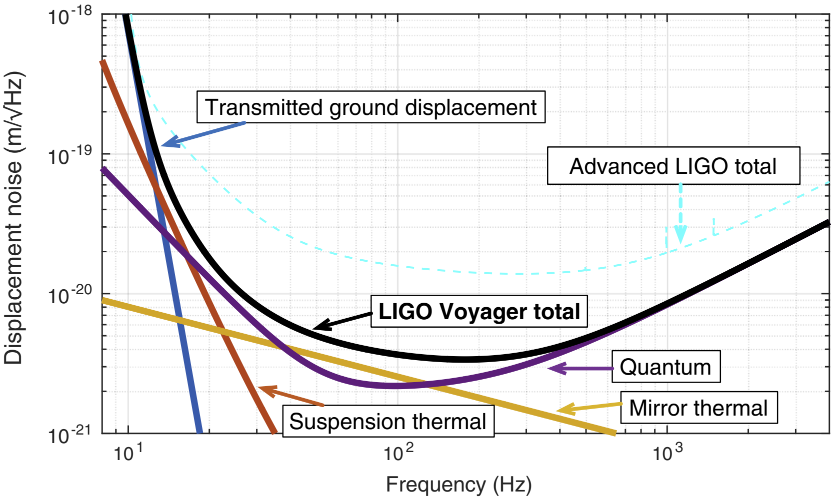

Fig. 1. The primary contributing noise sources for a possible LIGO Voyager interferometer design. Black, the predicted total displacement noise. Yellow, the thermal noise of the mirror surface. Red, the thermal noise associated with the suspension elements supporting the mirror. Blue, the transmission of ground displacements. Purple, quantum noise: high frequencies are shot noise, low frequencies are radiation pressure noise from photons bouncing off the mirror surfaces. Dashed cyan, a reference curve of the Advanced LIGO design noise. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)